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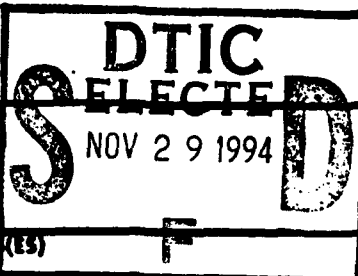
Robust Fixed-Structure Control

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13. ABSTRACT (Maximum 300 words)

This final report for AFOSR Grant F49620-92-J-0127 summarizes results obtained in five areas, namely, robust control, linear control, sampled-data control, tracking and disturbance rejection, and nonlinear control. Principal results include new bounds for the structured singular value, implementation of structured singular value synthesis using fixed-structure optimization techniques, a more rigorous foundation for the Maximum Entropy control technique, extensions of linear-quadratic control to stable stabilizing controllers, determination of the achievable performance of sampled-data controllers in the presence of sample-rate constraints, control of noise in an acoustic duct, stability theory for second-order systems, a rigorous treatment of Guyan reduction, a deterministic foundation for energy flow theory, a unified treatment of quadratic optimality and servocompensation, nonlinear control of the spinning top and rotating bodies with known and unknown mass imbalance, global stabilization of the oscillating eccentric rotor using integrator backstepping, and Lyapunov theory for finite-time convergence.

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1. Introduction

This Final Report marks the end of the third year of the 3-year cycle of AFOSR Grant F49620-92-J-0127. The first year of the Grant encompassed the period February 1992 to October 1992, the second year encompassed the period November 1992 through October 1993, and the third year encompassed the period November 1993 to September 1994. Research results from the first two periods are summarized in the Annual Reports dated November 1992 and November 1993. In this report we summarize results obtained throughout the entire program.

Attached to this report in Appendix A is a comprehensive bibliography listing all publications of the Principal Investigator. Part I covers journal papers and book chapters, while Part II covers conference publications. This list includes published papers, papers in press (denoted "to appear"), and papers submitted for publication. All of the listed papers corresponding to the time period of this grant, including papers submitted but not yet published, were supported at least partially by this grant.

Many of the results reported herein were obtained in collaboration with graduate student researchers at the University of Michigan some of whom were supported at varying levels under this Grant.

The outline of this proposal follows the original proposal which focused on five areas of research, namely, robust control, linear control, sampled-data control, tracking and disturbance rejection, and nonlinear control. Principal results include new bounds for the structured singular value, implementation of structured singular value synthesis using fixed-structure optimization techniques, a more rigorous foundation for the Maximum Entropy control technique, extensions of linear-quadratic control to stable stabilizing controllers, determination of the achievable performance of sampled-data controllers in the presence of sample-rate constraints, control of noise in an acoustic duct, stability theory for second-order systems, a rigorous treatment of Guyan reduction, a deterministic foundation for energy flow theory, a unified treatment of quadratic optimality and servocompensation, nonlinear control of the spinning top and rotating bodies with known and unknown mass imbalance, global stabilization of the oscillating eccentric rotor using integrator backstepping, and Lyapunov theory for finite-time convergence. These results are described in more detail in the following sections.

2. Summary of Technical Results

2.1 Robust Control

The major emphasis of this project was on robust control due to its relevance to control engineering applications. Our main line of work in this area has moved progressively from H_∞ theory, to positive real theory, to circle theory, to Popov theory, and, finally, to μ theory. After applying Popov-type theory to robust controller synthesis [I.91], we explored ties between structured singular value theory and classical absolute stability [I.81] which addresses the problems of nonlinear uncertainty and robust H_2 performance.

When used in the context of fixed-structure controller synthesis, the generalized Popov results provide an alternative to structured singular value synthesis by offering advantages over traditional D-K iteration. Specifically, by exploiting the cost gradients with respect to the parameterization of the multipliers, the controller, which may be of arbitrary fixed structure, can be determined concurrently with the multipliers. Although,

as with D-K iteration, it is not yet possible to prove convergence, the coupling of the controller and multiplier steps provides the possibility of significantly more efficient computations [I.107,I.115,I.116].

An alternative approach to robust control with constant real parameters is given by recent results obtained in [I.93]. In this paper we developed a novel frequency domain criterion that is distinct from structured singular value and absolute stability theory (such as Popov theory). Specifically, whereas structured singular value and absolute stability theory are based upon frequency-dependent circles in the Nyquist plane to guarantee robust stability, this new test guarantees stability by excluding the Nyquist plot from a *parabolic* region. For the case of two-sided uncertainty as in standard structured singular value and Popov theory, this condition has the form of a novel octomorphic (figure-eight shaped) inclusion criterion. Variations of this approach are explored in [II.130].

The advantage of the octomorphic criterion over standard structured singular value bounds is the fact that, due to its shape, the region is able to encompass the entire Nyquist plot. Thus it is not necessary as with circles to vary the region with frequency. Consequently, the scales needed to account for the multiple-block structure of the uncertainty are not required to be frequency dependent. This feature may allow considerable simplification in the implementation of real structured singular value bounds.

2.2 Linear Control

The fixed-structure approach has been used to synthesize linear controllers within the framework established by our robust control results as well as other design criteria. The fixed-structure approach provides considerable flexibility for synthesizing controllers of a desired feedback architecture, including order and decentralization. Although this approach does not lend itself easily to existence questions, it provides constructive techniques for obtaining controllers of interest. In contrast, conventional methods yield controllers only in special cases having more limited practical value.

In recent work we have addressed the problem of designing suboptimal controllers that are stable [I.83,I.86,I.87]. These results seek to overcome one of the drawbacks of optimal control techniques that may yield unstable controllers. Such unstable controllers are viewed by control-system practitioners as potentially dangerous for real-world applications. Our recent results offer significant improvements over earlier results we obtained in [I.51,II.48]. For example, the performance penalty for obtaining stable controllers has been reduced, and the new results yield reduced-order controllers as well.

Additional fixed-structure results motivated by practical issues are our results on designing positive real controllers [I.76]. These results, which extend an idea of other researchers to H_2/H_∞ control, allow the designer to obtain positive real controllers for flexible structure applications [I.96,I.111] where the sensors and actuators are colocated and dual. Since positive real controllers are also stable, these results are a refinement of the stable controllers mentioned above to a special class of problems. As an application of these positive real controllers, we developed an energy flow theory in [I.88,I.89,I.95] and used the positive real control approach to design energy flow controllers in [I.99,I.100].

To numerically implement these fixed-structure results, we have developed numerical optimization techniques. Two approaches have been considered. The first is a homotopy-based method being developed jointly with Professor L. T. Watson of Virginia Tech [I.60,I.61,I.98]. A parallel effort at the University of Michigan is based upon quasi-

Newton algorithms. To produce a reliable and widely applicable software package, we utilize the UNCMND package interfaced with Matlab routines. This code is being tested using laboratory data from a noise control experiment.

The code developed thus far applies to a general decentralized output feedback problem for H_2 and H_2/H_∞ controller synthesis. This code has been merged with the homotopy code developed at Virginia Tech to produce a more complete control design package. Extensions to structured singular value [I.116] and Maximum Entropy control design [I.66,I.90] are being developed.

2.3 Sampled-Data Control

Since modern controllers are usually implemented digitally, one of our goals has been to develop techniques for designing controllers that account precisely for sampling and discretization effects. Three topics in this area have been explored in recent work.

In [I.74] we explored problems that are inherent in designing sampled-data estimators for unstable plants. The main result is that the estimation cost is infinite unless the signal reconstruction device is a generalized hold extrapolator. This result thus focuses on a fundamental limitation of sampled-data systems.

In [I.79] we applied a periodic fixed-order approach to the problem of multi-rate estimation. This approach appears to be simpler and more straightforward than alternative approaches based upon lifting of the state space. More recently, the multi-rate control problem has been addressed using the fixed-order approach by Haddad and Kapila.

In [I.94] we carefully examined the dependence of achievable performance as a function of sample rate. By accounting precisely for all A/D and D/A effects as well as the discretization of the measurement noise, we were able to design a collection of controllers that range from continuous-time (infinitely fast sampling) to open-loop (infinitely slow sampling). These results demonstrate for the first time how the sampling rate affects the achievable closed-loop performance.

Finally, the use of exponential hold devices was examined in [II.118], while sampled-data control in the presence of transport delays was considered in [II.120].

2.4 Tracking and Disturbance Rejection

An important problem of practical interest involves tracking and disturbance rejection problems under various assumptions on the command and disturbance signals. The motivation behind this research is to improve system performance by exploiting specific knowledge concerning these signals. For example, a common control strategy is to employ internal models within the feedback controller to achieve asymptotic command following or disturbance rejection. This approach is called servocompensation and disturbance accommodation.

Thus far we have merged H_2 theory with servocompensator design to examine fundamental tradeoffs between these two objectives [I.103]. Dual results for disturbance accommodation follow analogously [I.105,I.106]. In both cases we apply fixed-structure optimization techniques to determine optimal controller gains.

Work in progress in this area includes adaptive tracking and disturbance accommodation of partially uncertain signals such as sinusoids with uncertain frequency. This work extends the servocompensation theory which allows uncertain phase and amplitude, but requires precise knowledge of frequency.

2.5 Nonlinear Control

As linear control theory becomes increasingly well-understood, there remains the challenge of designing nonlinear controllers that can improve performance beyond the best linear controllers. In fact, most implemented controllers are actually nonlinear due to mode switching and other effects. Hence, a major area of emphasis of this program has been the development of nonlinear control methods that are applicable to problems of engineering interest. Our main goal is to develop control methods that have sufficiently broad applicability to address real world constraints and models.

The results we have obtained thus far exploit the relationship between Lyapunov function theory and Hamilton-Jacobi-Bellman theory. In particular, by focusing on steady-state problems, we exploit the fact that the solution to the HJB equation is a Lyapunov function for the closed-loop system [I.68]. The key step is to exploit the relationship between the cost functional, the Lyapunov function, and the plant dynamics. In certain cases, families of nonlinear feedback control laws can be found as solutions to the HJB equation. This approach was used in [I.92] to obtain a class of nonlinear control laws that globally stabilize angular velocity with only two torque actuators. These results include controllers obtained by other researchers as special cases and showed, for the first time, that the zero dynamics structure plays a role in finding solutions to the HJB equation.

As another application of HJB theory, we considered in [I.85] the problem of feedback control with multiple saturating actuators. For this practical problem, we showed that continuous saturating nonlinear control laws are optimal for a modified cost functional having different definitions in the nonsaturating and saturating regions. These results are an improvement over known results involving discontinuous controllers.

In related results concerning the saturation problem, we obtained novel results pertaining to a wide class of input nonlinearities, including saturation as a special case [I.78]. These results are valid for the limited, but practical, class of positive real plants subjected to positive real controllers. By using a nonlinear modification of the controller, we showed using Lyapunov methods that the closed-loop system can be guaranteed to be stable in spite of the input nonlinearity. This approach was demonstrated for the problem of integrator windup which arises with PI controllers. By suppressing integrator windup, the nonlinear controller is less prone to the effects of actuator saturation. This approach appears to be the first anti-windup scheme that is based upon Lyapunov stability theory.

Further results on control of plants with saturation were obtained in [I.104] which applied small-gain type techniques to guarantee closed-loop stability. A novel feature of these results is the elimination of a priori assumptions on the amplitude of the state or magnitude of control. A modified Lyapunov-type argument was used to guarantee stability without excessive conservatism.

Nonlinear controllers were obtained for a challenging nonlinear mechanical system known as the oscillating eccentric rotor. Stabilizing controllers were obtained by applying integrator backstepping techniques [I.109]. The performance of these controllers and the required control effort were compared to the use of passive controllers in [II.108]. This comparison uses insight obtained from our work on energy flow theory [I.88, I.89, I.95].

As another challenging problem in nonlinear control, we considered the control of the spinning top under a variety of actuation schemes [I.97,I.101]. More recently, we considered the case in which the top is asymmetric and/or possesses mass imbalance [I.113]. This work provided the basis for considering the practical problem of stabilizing a rotating body with unknown mass imbalance [I.114].

Finally, we studied a class of nonlinear controllers having the property of driving the state to the origin in finite time [II.122]. These controllers are of interest in practical situations involving mechanical contact without collision.

Appendix A
Publications of the Principal Investigator

I. Journal Papers and Book Chapters

- I.1 D. S. Bernstein, "The Treatment of Inputs in Real-Time Digital Simulation," *Simulation*, Vol. 33, No. 2, pp. 65-68, 1979.
- I.2 D. S. Bernstein and E. G. Gilbert, "Optimal Periodic Control: The Pi Test Revisited," *IEEE Trans. Autom. Contr.*, Vol. AC-25, pp. 673-684, 1980.
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